

Location and origin of gamma-rays in blazars

B. Rani, T. P. Krichbaum, J. A. Hodgson, J. A. Zensus

Max-Planck-Institut für Radioastronomie (MPIfR), Auf dem Hügel 69, D-53121 Bonn, Germany

E-mail: brani@mpifr-bonn.mpg.de

On behalf of the *Fermi*-LAT Collaboration

Abstract. One of the most intriguing and challenging quests of current astrophysics is to understand the physical conditions and processes responsible for production of high-energy particles, and emission of γ -rays. A combination of high-resolution Very Long Baseline Interferometry (VLBI) images with broadband flux variability measurements is a unique way to probe the emission mechanisms at the bases of jets. Our analysis of γ -ray flux variability observed by the *Fermi*-LAT (Large Area Telescope) along with the parsec-scale jet kinematics suggests that the γ -ray emission in blazar S5 0716+714 has a significant correlation with the mm-VLBI core flux and the orientation of jet outflow on parsec scales. These results indicate that the inner jet morphology has a tight connection with the observed γ -ray flares. An overview of our current understanding on high-energy radiation processes, their origin, and location is presented here.

1. Introduction

The origin of high-energy emission has long been a key question in Active Galactic Nuclei (AGN) physics. While they represent only a minority of AGN, blazars constitute a unique laboratory to probe the acceleration processes in relativistic jets emanating from the central engine. Since its launch in 2008, the *Fermi*-LAT (Large Area Telescope) has revolutionized our knowledge of the γ -ray sky with a combination of high sensitivity, wide field-of-view, and a large energy range (about 20 MeV to more than 300 GeV). Its nominal sky-survey operating mode has enabled a continuous monitoring of the complete γ -ray sky at an unprecedented level, making remarkable discoveries. The third *Fermi*-LAT catalog (3FGL, Acero et al., 2015), based on the first 48 months of data, consists of more than 3000 γ -ray sources including $\sim 60\%$ AGN - most of which are blazars ($\sim 98\%$ Ackermann et al., 2015). Blazars therefore form a major population of the γ -ray sky and are potential targets for understanding the physical processes responsible for production of high-energy emission. Moreover, blazars also account for the majority of the high energy γ -ray background above 100 GeV (Ajello et al., 2015).

BL Lacertae objects (BL Lacs) and flat spectrum radio quasars (FSRQs) are clubbed together and called blazars. In spite of the dissimilarity of their optical spectra – FSRQs show strong broad emission lines, while BL Lacs have only weak or no emission lines in their optical spectra – they share the same peculiar continuum properties (strong variability and polarization properties). They are characterized by powerful non-thermal emission ranging from radio to the γ -ray bands and exhibit strong variability, over a variety of time scales from minutes to

months and often the radio components detected in VLBI observations exhibit superluminal motion. These properties are interpreted as resulting from the emission of high-energy particles accelerated within a relativistic jet aligned with the direction of sight. In many cases, the bulk of the observed flux emerges in γ -ray photons in GeV (TeV for some sources) energy range populating a major fraction of the high-energy sky (Ackermann et al., 2015; Acero et al., 2015). One of the most intriguing and challenging quests of current astrophysics is to understand the physical conditions and processes responsible for the production of high-energy particles, and the emission of γ -rays.

2. Particles accelerated in relativistic jets

Detailed investigation of multi-wavelength flux and spectral variability of individual sources including cross-band (radio, optical, X-ray, γ -ray, and polarization), relative timing analyses of outbursts, and/or VLBI component ejection/kinematics suggest that γ -rays are associated with the compact regions of relativistic jets energized by the central SMBHs (e.g., Agudo et al., 2011; Jorstad et al., 2001, 2010; Marscher et al., 2010; Schinzel et al., 2012; Rani et al., 2013a, 2015, and references therein). For individual objects, the close association of the γ -ray flare with a continuous change of the optical polarization angle provides evidence for the presence of highly ordered magnetic fields in the regions of γ -ray production (Abdo et al., 2010; Marscher et al., 2008). Recent studies (at least for some blazars) suggest a significant correlation between the variations of γ -ray flux and the direction of the jet outflow in the sub-parsec scale region (Rani et al., 2014), which implies that the observed inner jet morphology has a strong connection with the observed γ -ray flares. However, the fine details of acceleration mechanisms and radiation processes are still missing.

Blazars exhibit a characteristic bimodal spectral energy distribution (SED). The SED low-energy peak (from radio to optical/UV and X-rays for some sources) is commonly interpreted as synchrotron emission from high-energy electrons, while no consensus on the origin of the high-energy peak (from X-rays to γ -rays) has been reached. In the framework of leptonic models, this second peak corresponds to photons produced via inverse-Compton scattering of soft seed photons by the same electrons, with these seed photons originating either from within the jet (Synchrotron Self-Compton, SSC) or from regions external to the jet, such as the accretion disk, the dust torus or the broad emission line clouds (External Compton, EC). In hadronic models, the high energy peak is due to photons produced in photo-hadron interactions or by proton or charged μ/π synchrotron emission and subsequent cascades (e.g., Böttcher et al., 2007, 2012, 2013). Concerning the high-energy emission, leptonic models are more favored in the literature; however, hadronic processes remain a viable option.

No clear consensus has been achieved on the location of emission regions. The radio- γ -ray correlations (Fuhrmann et al., 2014; Marscher et al., 2008, 2010; Rani et al., 2013a) suggests the latter leading the former, which puts the location of high-energy emission regions closer to the central black hole. The observed γ -ray spectral breaks at a few GeVs require the emitting region to be located within the BLR if the photon-photon pair production scenarios are responsible for their origin (Abdo et al., 2009; Finke & Dermer, 2010; Rani et al., 2013b,c; Poutanen & Stern, 2010). On the other hand, coincidence of γ -ray flares with the appearance of new components from the base of the jet indicates distances longer than few parsecs (Jorstad et al., 2013; Agudo et al., 2011; Schinzel et al., 2012). Interaction of moving features with the stationary features can amplify the magnetic field and accelerate particles (Marscher, 2014). Coincidence of γ -ray flares with the passage of moving components through stationary features in jets has been observed in several sources (Schinzel et al., 2012; Rani et al., 2015), which implies that γ -ray flares are produced downstream of the core at a distance of more than a few parsecs.

Particle acceleration in relativistic jets is also an open question. Relativistic shocks seem to be effective in low magnetization regimes; however in the case of high magnetization, shocks

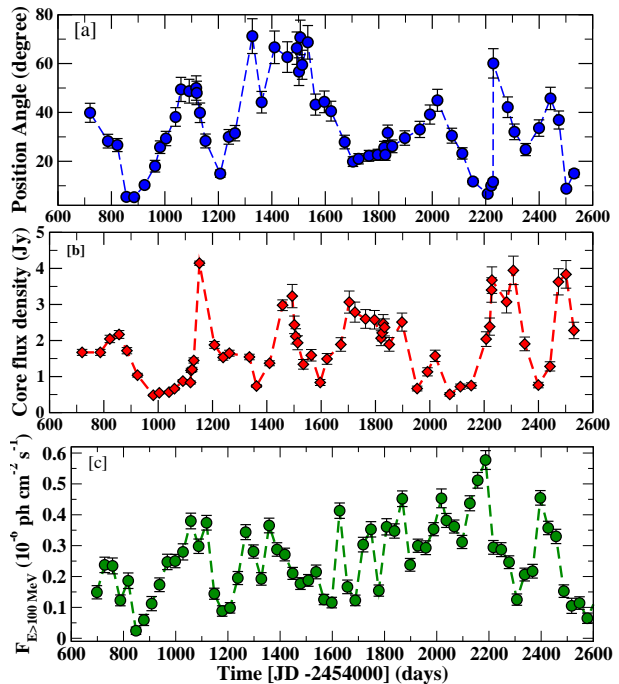
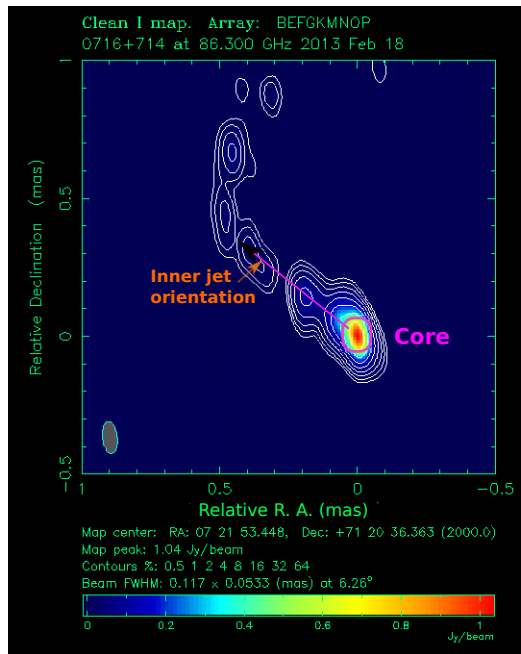


Figure 1. Left: The 86 GHz VLBI image of S5 0716+714 observed on February 18, 2013. Right: (a) Orientation variations in inner region (≤ 0.2 mas) of the jet, (b) the 7 mm VLBI core flux density variations, and (c) the monthly averaged γ -ray photon flux light curve.

are weak and poor accelerators. Particle acceleration through second order stochastic processes is rather slow in highly magnetized flows; but it is still a viable option (Blandford, 1973). In highly magnetized environments, particle acceleration via magnetic reconnection is very likely to occur (Kagan et al., 2015). Most likely all of these processes are in action on different scales in jets. Closer to the central engines, magnetic reconnection could inject energetic particles in compact regions to produce rapid γ -ray flares. Further downstream the jet in low magnetized environments, the observed γ -ray variations could be a natural consequence of relativistic shocks. Magnetoluminescence and/or electromagnetic detonation is lately proposed to explain the fastest observed TeV flares. The basic idea is that the tightly wound magnetic field in the inner jet regions is subject to dynamical instability which could be responsible for the rapid γ -ray variability. In other words, impulsive particle acceleration can take place while the magnetic flux ropes untangle (Blandford et al., 2015), which could be responsible for high-energy flares.

3. Causal connection between gamma-ray emission and jet morphology

Our recent studies on the BL Lac S5 0716+714 suggest a significant correlation between the variations of γ -ray flux and the direction of the jet outflow in sub-parsec scale region (see Rani et al., 2014, for details). The core flux density and inner-jet orientation (position angle) variations were investigated using the 7 millimeter Very Long Baseline Interferometry (VLBI) observations of S5 0716+714 for a time period between August 2008 and September 2013. In Fig. 1 (left), we show an example map of the source. The variations in the core flux density and orientation of the sub-parsec scale jet i.e. position angle (PA) are shown in Fig. 1 (a and b). The γ -ray flux variations (Fig. 1 c) over the same time period were examined using the observations obtained by the *Fermi*-LAT (Large Area Telescope).

The discrete cross-correlation function (DCF, Edelson & Krolik, 1988) method was used to investigate the correlation between the observed γ -ray and jet morphology (core flux density and

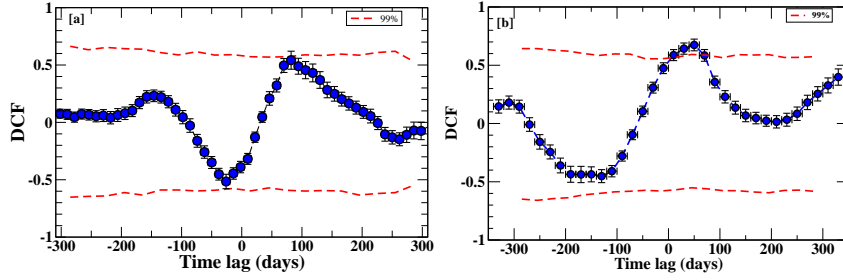


Figure 2. Cross-correlation analysis curves: γ -ray vs. core flux density (a) and γ -ray vs. position angle (b). The dashed lines show the 99% confidence levels.

PA) variations. The DCF analysis results are presented in Fig. 3. The analysis suggests that the high-energy radiation has a tight correlation between the VLBI core flux density and the direction of the jet flow (Fig. 3). We observed a time lag of 82 ± 39 days between γ -ray and core flux density variations, which puts the location of γ -ray emission region upstream of the 7 mm VLBI core by 3.8 ± 1.9 pc (de-projected). Given the location of the 7 mm core at a distance of ~ 6.5 pc (Rani et al., 2015), we conclude that the γ -ray emission region is at a distance of 2.7 ± 1.9 pc from the central engine. The correlated variations observed in the innermost PA and the high-energy flux of S5 0716+714 add a unique new point to constrain the location and origin of high-energy emission in blazars.

4. Future Perspectives

High-frequency VLBI is a promising technique to pinpoint the high-energy emission sites. With the current GMVA (Global mm-VLBI Array) resolution at 86 GHz frequency ($\sim 50 \mu\text{as}$), one could scale down to less than a thousand Schwarzschild radii. The Event Horizon Telescope (EHT) will offer an angular resolution of $\sim 20 \mu\text{as}$, which means that the future of high-resolution VLBI is very bright. Participation of ALMA will bring a revolutionary leap in capabilities for mm-VLBI. The *Fermi* mission with its extraordinary capabilities will keep observing the γ -ray sky at least for the next few years. In the upcoming years, TeV astronomy will also grow making several more new and major discoveries. Not to mention, high-energy polarization missions (Astro-H, GEMS, X-calibur, PoGOLite, Polar, Harpo, and many more) are also on their way to teach us more about high-energy emission models.

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